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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Characterisation framework development for the SIMPASS (Singapore IMPact ASSessment) methodology

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Abstract
Purpose Life cycle assessment (LCA) practitioners in Singapore currently rely on foreign life cycle impact assessment (LCIA) methodologies when conducting studies, despite the fact that foreign methodologies may not be relevant, adaptable and sensitive to Singapore's circumstances. As a result, work has been undertaken to develop the Singapore IMPact ASSessment (SIMPASS) methodology by adapting and modifying existing LCIA methodologies to suit the Singaporean context. It is envisioned that the use of SIMPASS will improve the accuracy of LCA studies conducted for industries operating in Singapore.
Methods The development is initiated by a compendious review of the available LCIA methodologies, in order to familiarise state-of-the-art developments and best available practice for LCIA in the world. Subsequently, five key design considerations are discussed. Firstly, six impact categories (climate change, acidification, eutrophication, fossil fuel depletion, water use and land use) are identified and prioritised for detailed analysis in this project, in view of their relevance and criticality to Singapore. Subsequently, user issues and the type of LCIA approach are considered. Following which, four areas of protection (namely Human Health, Natural Environment, Natural Resources and Man-made Environment) are selected for consideration in the SIMPASS methodology.
Results With the development approach in mind, extensive research is conducted in the six selected impact categories to construct the characterisation framework for SIMPASS. The characterisation framework is strongly based on current best practices in LCIA characterisation, while the characterisation models are chosen based on their extent of comprehensiveness, scientific sophistication, as well as specificity to Singapore.
Conclusions and recommendations SIMPASS proposes an attractive and feasible LCIA methodology that is highly specific to Singapore. Feasible recommendations are drawn to further develop and operationalise the characterisation framework.

Keywords Life cycle impact assessment · Singapore · Climate change · Acidification · Eutrophication · Fossil fuel depletion · Water use · Land use

Abbreviations

CF	Characterisation factor
CI	Category indicator
ILCD	International Reference Life Cycle Data Systems
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
SIMPASS	Singapore Impact Assessment

1 Introduction

While it is possible to use existing life cycle impact assessment (LCIA) methodologies on life cycle assessment (LCA) studies conducted in Singapore, there are notable

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limitations on the usage of foreign LCIA methodologies. Firstly and most importantly, foreign LCIA modelling may not be applicable for the unique Singaporean environmental circumstances, resource endowment, as well as the variance in Singaporean ecosystems. Normalisation and weighting procedures may also experience difficulty in adapting to Singaporean conditions, due to the mismatch in background information, social, cultural and political differences in the foreign LCIA methodologies (Brent and Hietkamp 2003). On the other hand, there are significant benefits in the development of Singapore's very own LCIA methodology. In Singapore, the Environmental Management Standards Committee has formed a focus group on LCA in 2002 to 'consider the applications and use of LCA, especially in environmental labelling programmes, in design for environment, in environmental performance evaluation and environmental improvement programmes, and in national decision making for environmental-related matters' (Tan 2003). Therefore, it is imperative that a Singaporean version of the LCIA methodology be developed to provide a better representation of the local scenario. The accuracy of Singaporean LCA studies conducted for industries operating in Singapore is expected to be enhanced as a result.

Hence, the Singapore IMPact ASSessment (SIMPASS) methodology has originated from the above motivations. The following paper focuses on the characterisation development approach, the characterisation models and general characterisation factor equations adapted for SIMPASS. Detailed specifications and calculation procedures, which can be found in specific papers, have been omitted.

2 Design considerations

2.1 Selection of impact categories

The selection of the impact categories to be considered in SIMPASS is a key design consideration for two reasons. Firstly, the unique environmental circumstances of Singapore have resulted in a unique set of impact categories that are relevant to the country, such as the issues of water resource, scarcity of land, solid waste management and human health (Tan 2003). Secondly, while it is important to include the global impact categories (such as climate change), current attention and effort should be directed towards regional and local impact categories that require a high degree of spatial modelling and differentiation. The small geographical size of Singapore indicates that impact categories on a local or regional level are more relevant in this project than those on a global level. Furthermore, global impact categories have universally accepted modelling protocols and frameworks which will be easy to interface within SIMPASS in the future. As a first step, the decision is to select climate change, acidification, eutrophication, fossil fuel depletion, water use and land use as impact categories to be considered in this study. Other relevant impact categories, such as ecotoxicity and human toxicity, are left for the next stage of development. Although they do not fall within the scope of this preliminary work, they will be included eventually into SIMPASS. This will be done after reviewing their respective current best practices, such as the USEtox model for human and ecotoxicity characterisation (Rosenbaum et al. 2008).

2.2 User issues

Referring to the International Reference Life Cycle Data Systems (ILCD) Handbook (ILCD 2010), SIMPASS should be developed with the following criteria in mind: completeness of scope; environmental relevance; scientific robustness and certainty; documentation, transparency and reproducibility; applicability, as well as stakeholder acceptance. The above criteria will be emphasised throughout the future development of SIMPASS. It is also recommended that the future developers conduct a preliminary survey on the potential users of SIMPASS to have an accurate gauge on their concerns and requirements of the methodology.

2.3 Midpoint versus endpoint approaches

In essence, midpoint approaches represent greater reliability, while endpoint approaches represent greater relevancy. Faced with the merits and limitations of both approaches, there is a consensus among LCA experts around the world that 'both set of results (from midpoint and endpoint approaches) should be presented, either in a parallel or tiered approach, within one consistent framework' (Bare et al. 2000). The same recommendation is employed for SIMPASS throughout its stages of development. Nevertheless, it is envisaged that SIMPASS may try to adopt a predominantly midpoint-oriented approach first, thus availing itself the opportunities of scientific validation. This will allow time to eliminate the associated data uncertainties and assumptions in order to properly develop the endpoint approach. SIMPASS can then be extrapolated into an endpoint approach, while carefully addressing any resulting loss of reliability in the process.

2.4 Selection of AoPs

Areas of protection (AoP), although generally classified into four groups (Human Health, Natural Environment, Natural Resources and Man-made Environment), vary slightly in definition across different LCIA methodologies. However, the above classification is widely considered to be the most successful to 'comprehensively, yet concisely

categorise the several variations of AoPs' (Bare and Gloria 2006). It is recommended that SIMPASS include the AoPs of Human Health, Natural Environment and Natural Resources. The AoP for Man-made Environment may be regarded as a minor consideration at the moment due to the lack of societal and scientific consensus in quantifying impacts, but may warrant future evaluation when proven to be necessary.

3 The SIMPASS characterisation framework

As mentioned in an earlier section, six impact categories are prioritised for consideration in the SIMPASS characterisation framework (climate change, acidification, eutrophication, fossil fuel depletion, water use and land use). The proposed SIMPASS characterisation framework is presented in Fig. 1, while the main aspects of the SIMPASS methodology (characterisation models and general characterisation factor equations recommended) are presented in Table 1. With reference to Table 1, the general characterisation factor equation for a particular elementary flow of type x and magnitude m is generally expressed in the following form:

$$\text{Category Indicator (CI)} = \sum\nolimits_{x} \left[\mathrm{m_x} \times \text{Characterisation Factor}\,(\mathrm{CF_x})\right] \quad (1)$$

Comprehensive analyses of the impact categories' relevance to Singapore, possible elementary flows, environmental impacts, relevant characterisation models, current regulation and future policies in Singapore are conducted. The proposed SIMPASS characterisation framework is strongly based on current best practices in LCIA characterisation (Udo de Haes HA et al. 2002), while the characterisation models are chosen based on their extent of comprehensiveness, scientific sophistication, as well as specificity to Singapore.

3.1 Climate change

It is recommended that the model developed by the Intergovernmental Panel on Climate Change defining the global-warming potential of different greenhouse gases be integrated into SIMPASS, given its widespread scientific acceptance (IPCC 2007).

In line with the recommended best practices (Udo de Haes HA et al. 2002), the global-warming potentials of each greenhouse emission x (GWP_x) will be calculated using the model to serve as the CFs, which are selected at the category midpoint level for a 100-year time horizon. Subsequently, using the general characterisation factor equation, climate change can then be computed as the CI, at the category endpoint levels of damages to human health, aquatic and terrestrial ecosystem. The work by De Schryver et al. (2009) will be used to guide the quantified damages of climate change impacts to the endpoint levels. Lastly, the environ-

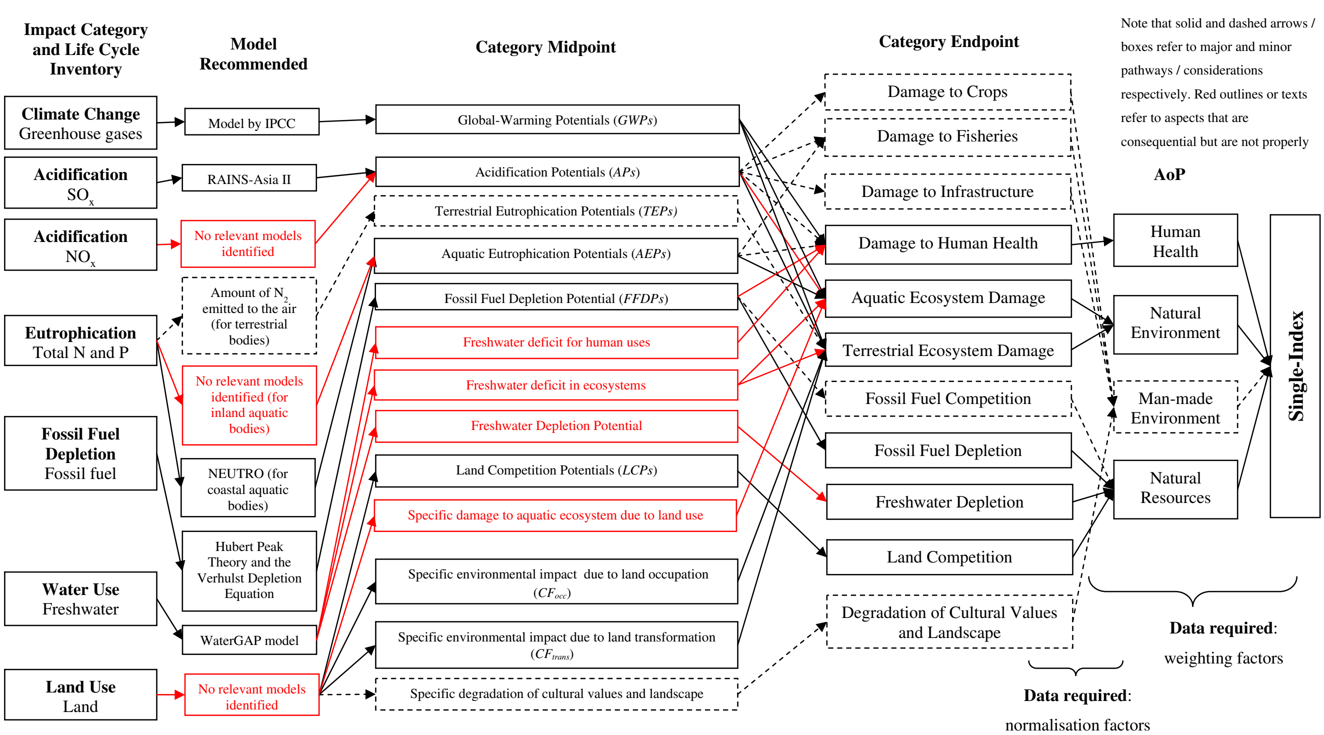

Fig. 1 The proposed SIMPASS characterisation framework

Table 1 Details of characterisation models and general characterisation factor equations recommended

Impact category	Elementary flow	Characterisation model recommended	Comments	Category midpoint	General characterisation factor equation	Category endpoint	AoP
Climate change	Climate gases	The model developed by the Intergovernmental Panel on Climate Change (IPCC) defining the global warming potential of different greenhouse gases (IPCC 2007)	Widespread scientific acceptance	Global-warming potential (GWP)	Climate change = $\sum_x (m_x \times \mathrm{GWP}_x)$	Damage to human health	Human health
						Terrestrial ecosystem damage	Natural environment
						Aquatic ecosystem damage	
Acidification	SO_x	RAINS-Asia II (Downing et al. 1997)	Spatially differentiated, option for source selection	Acidification potential (AP)	$\mathrm{AP} = \sum_x (m_x \times \mathrm{AP}_x)$	Aquatic ecosystem damage	Natural environment
	NO_x	No relevant model identified	Need to create a model for NO_x			Terrestrial ecosystem damage	
Eutrophication	Total N and P	Neutro (PORL 2008)	Spatially differentiated, option for source selection. Need to consider inland aquatic eutrophication.	Aquatic eutrophication potential (AEP)	$\mathrm{AEP} = \sum_x (m_x \times \mathrm{AEP}_x)$	Aquatic ecosystem damage	
		No relevant model identified	Need to create a model for inland aquatic bodies				
		Amount of N_2 emitted to the air (Udo de Haes et al. 2002)	Simplistic way to characterise terrestrial eutrophication, lack of spatial differentiation	Terrestrial eutrophication potential (TEP)	$\mathrm{TEP} = \sum_x (m_x \times \mathrm{TEP}_x)$	Terrestrial ecosystem damage	
Fossil fuel depletion	Fossil fuels (coal, oil and natural gas)	Hubbert Peak Theory and the Verhulst Depletion Equation (Roper 1976)	Widely accepted scientifically	Fossil fuel depletion potential (FFDP)	$\mathrm{FFDP} = \sum_x (m_x \times \mathrm{FFDP}_x)$	Fossil fuel depletion	Natural resources
					None recommended	Damage to human health	Human health
Water use	Freshwater	WaterGAP model (CESR 2010)	Use of GIS allows data processing and statistical evaluation on different spatial resolutions	Freshwater deficits for human uses	None recommended	Damage to human health	Human health
				Freshwater deficits in ecosystems		Terrestrial ecosystem damage	Natural environment
						Aquatic ecosystem damage	
				Freshwater depletion potential		Freshwater depletion	Natural resources
Land use	Land	Land occupation and transformation	Need to create a biogeographical land	Specific environmental	$\mathrm{CI}_{occ} = \mathrm{CF}_{occ} \times \Delta t_{occ} \times A_{occ}$	Terrestrial ecosystem damage	Natural environment

Table 1 (continued)

Impact category	Elementary flow	Characterisation model recommended	Comments	Category midpoint	General characterisation factor equation	Category endpoint	AoP
		model (Guinee et al. 2001)	use model specific to Singapore	impact due to land occupation (CI_{occ})			
				Specific environmental impact due to land transformation ($CI_{trans,n\text{-}1\rightarrow n}$)	$CI_{trans,n\text{-}1\rightarrow n}=CF_{trans,n\text{-}1\rightarrow n}\ x\ A_{trans}$		
				Specific damage to aquatic ecosystem due to land use	None recommended	Aquatic ecosystem damage	
				Land competition potential (LCP)	$LCP = \sum_x (LCP_x \times a_x)$	Land competition	Natural resources

mental impacts of climate change in Singapore are classified into the AoPs Natural Environment and Human Health. The features and specifications for climate change characterisation are summarised in Table 1 and Fig. 1, as well as in Table E.1 of the Electronic supplementary information.

3.2 Acidification

It is recommended that the Regional Air Pollution Information and Simulation Model for Asia (RAINS-Asia) model be integrated into SIMPASS, given the numerous features and high degree of geographical relevance that are offered by this model. The RAINS-Asia model is an assessment tool dedicated to the understanding of acid rain in Asia and to assist in the development of strategies to mitigate or eliminate the problem (Downing et al. 1997).

In line with the recommended best practices (Udo de Haes HA et al. 2002), acidification potentials of each acidifying emission x (AP_x) will be calculated using the RAINS-Asia model to serve as the CFs, which are selected at the category midpoint level. Using the general characterisation factor equation, acidification potential (AP) can then be computed as the CI, at the category endpoint levels of Aquatic and Terrestrial Ecosystem Damages. Lastly, the environmental impacts of acidification in Singapore are classified into the AoPs Natural Environment, Man-made Environment and Human Health. However, AoP Human Health and Man-made Environment will be assumed to be negligible in this preliminary framework, due to the lack of relevance and documented acidification effects in Singapore. The features and specifications for acidification characterisation are summarised in Table 1 and Fig. 1, as well as in Table E.2 of the Electronic supplementary information.

3.3 Eutrophication

For aquatic eutrophication, it is recommended that the NEUTRO model be integrated into SIMPASS, given the numerous features and high degree of geographical relevance that are offered by this model. NEUTRO has the capability of conducting impact assessment for industrial developments and anthropogenic spills in Singaporean coastal zones, and to predict the water quality of Singapore waters with respect to nutrients, phytoplankton, dissolved oxygen, suspended solids as well as bacteria decay (PORL 2008).

For terrestrial eutrophication, the amount of nitrogen emitted to the air will be used as a simplistic indicator. Nevertheless, this arrangement should be sufficient due to the low occurrence of terrestrial eutrophication in Singapore and the lack of coverage given to characterising it in LCIA. In line with the recommended best practices (Udo de Haes HA et al. 2002), aquatic eutrophication potentials of each eutrophication-contributing emission x (AEP_x) will be calcu-

lated using the NEUTRO model to serve as the CF for aquatic eutrophication. Similarly, terrestrial eutrophication potentials of each eutrophication-contributing emission x (TEP_x) will be calculated using the amount of N_2 emitted to the air as a modelling basis to serve as the CF for terrestrial eutrophication. These CFs are selected at the category midpoint level. Using the respective general characterisation factor equations, aquatic and terrestrial eutrophication potentials (AEP and TEP) can then be computed as the CIs, at the category endpoint level of Aquatic and Terrestrial Ecosystem Damages. Lastly, the environmental impacts of eutrophication in Singapore are classified into the AoPs Natural Environment, Man-made Environment and Human Health. However, AoP Human Health and Man-made Environment will be assumed to be negligible in this preliminary framework, due to the lack of relevance and documented eutrophication effects in Singapore. The features and specifications for eutrophication characterisation are summarised in Table 1 and Fig. 1, as well as in Table E.3 of the Electronic supplementary information.

3.4 Fossil fuel depletion

It is recommended that the Hubbert Peak Theory and the Verhulst Depletion Equation (Roper 1976) be integrated in the SIMPASS methodology in order to calculate values for the fossil fuels' ultimate reserves (R) and rates of extraction (DR). In line with the recommended practices, fossil fuel depletion potentials of each fossil fuel x ($FFDP_x$) will be calculated using the above R and DR values to serve as the CF for fossil fuel depletion, which is selected at the category midpoint level. Using the general characterisation factor equation adopted from the CML 2001 methodology (Guinee et al. 2001), Fossil Fuel Depletion Potential (FFDP) can then be computed as the CI, at the category endpoint level of Fossil Fuel Depletion. Nevertheless, Fossil Fuel Competition has not been considered as a category endpoint in this proposed characterisation framework, in line with the recommendations by current LCIA best practices (Udo de Haes HA et al. 2002). Lastly, the environmental impacts of fossil fuel depletion in Singapore are classified into the AoPs Natural Resources and Human Health. However, the AoP Human Health will not be considered in this preliminary framework due to the lack of international expert consensus in this area. The features and specifications for fossil fuel depletion characterisation are summarised in Table 1 and Fig. 1, as well as in Table E.4 of the Electronic supplementary information.

3.5 Water use

The suggested characterisation framework for water use is based on the work by Bayart et al. (2010). Furthermore, it is recommended that the WaterGAP (Water-Global Assessment and Prognosis) model (CESR 2010) be integrated into SIMPASS in order to factor in geographically specific modelling in SIMPASS, as suggested by Pfister et al. (2009). The WaterGAP model is able to compare and assess current water resources and water use in different parts of the world, and to provide an integrated long-term perspective of the impacts of global change on the water sector.

In line with the above suggested characterisation approach (Bayart et al. 2010), the relevant category endpoint levels are Damage to Human Health, Terrestrial Ecosystem Damage, Aquatic Ecosystem Damage and Freshwater Depletion. Lastly, the environmental impact of water use in Singapore is classified into the AoPs Human Health, Natural Environment and Natural Resources, as seen in Fig. 1. As the proposed method remains under development, detailed general characterisation factor equations are currently not available. The features and specifications for water use characterisation are summarised in Table 1 and Fig. 1, as well as in Table E.5 of the Electronic supplementary information.

While it is acknowledged that there is some intersection between water use and land use characterisation methods, this will only be further examined in the later development stages of SIMPASS.

3.6 Land use

While there is currently a notable dearth of simulation models that is specific to land use in Singapore, the land quality change model is the best developed land use LCIA method available currently, because it is able to calculate the impact of land occupation and transformation by the comprehensive consideration of land use area, duration and land quality change (Liu et al. 2010).

In line with this suggested land use characterisation approach (Guinee et al. 2001), the relevant land use CFs can be calculated from parameters as listed in the Table E.8 of the Electronic supplementary information. Subsequently, using the appropriate general characterisation factor equations, the respective CIs at the category endpoint levels of Terrestrial Ecosystem Damage, Aquatic Ecosystem Damage and Land Competition can then be computed. Notably for Land Competition, an innovative approach was adopted by regarding land in Singapore as a type of depletable resource, resulting in the implementation of a general characterisation factor equation that is modified from that of Fossil Fuel Depletion in the CML 2001 methodology, as seen from Table 1. It is proposed that the land competition potential of each land type x (LCP_x) will be calculated using the parameters of maximum land area (R_x), the yearly amount of land type

x used for human purposes in Singapore (DR_x) and appropriate reference states (R_{ref} and DR_{ref}) to serve as the CF:

$$LCP_x = \left(DR_x/R_x^2\right)/\left(DR_{ref}/R_{ref}^2\right) \quad (2)$$

Lastly, the environmental impact of land use in Singapore is classified into three AoPs Natural Environment, Natural Resources and Man-made Environment. However, damages to Man-made Environment are again assumed to be negligible since the definition and variation of cultural and aesthetic goods varies widely amongst the members of the Singaporean society currently. The features and specifications for land use characterisation are summarised in Table 1 and Fig. 1, as well as in Table E.6 of the Electronic supplementary information.

Furthermore, there remains a significant controversy on which indicator for land quality (Q) to be used (Udo de Haes HA et al. 2002). As this framework does not aim to recommend a single indicator for Singapore in view of the controversial nature of the selection, the evaluation and decision of the indicator will be left for future research and development.

4 Conclusions and recommendations

SIMPASS proposes an attractive and feasible LCIA methodology that is expected to be highly specific to Singapore. Recommendations to further develop and operationalise the characterisation framework have been drawn. Firstly, in order to develop SIMPASS in accordance to international standards, the ILCD criteria are recommended as the evaluation criteria (ILCD 2010). The criteria will direct the future development and operationalisation of SIMPASS. The results will also be presented in future case studies. Secondly, there is a need to develop an acidification characterisation model for oxides of nitrogen, a characterisation model that considers inland aquatic eutrophication, an operational water use characterisation model and a Singapore-specific land use characterisation model. At the level of the category midpoint, damage to aquatic ecosystem due to land use demands further research attention. At the level of AoP, Man-made Environment and its associated category endpoints are the underdeveloped portions of the framework due to the lack of societal and scientific consensus in quantifying impacts. Additionally, future work focusing on different models for midpoint and endpoint indicators (shown in Tables E.1–E.6) will be considered for SIMPASS.

References

Bare JC, Gloria TP (2006) Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches. Environ Sci Tech 40(4):1104–1113

Bare JC, Hofstetter P, Pennington DW, Udo de Haes HA (2000) Life cycle impact assessment workshop summary. Midpoints versus endpoints: the sacrifices and benefits. Int J Life Cycle Assess 5 (6):319–326

Bayart JB, Bulle C, Deschênes L, Margni M, Pfister S, Vince F, Koehler A (2010) A framework for assessing off-stream freshwater use in LCA. Int J Life Cycle Assess 15(5):439–453

Brent AC, Hietkamp S (2003) Comparative evaluation of life cycle impact assessment methods with a South African case study. Int J Life Cycle Assess 8(1):27–38

CESR (2010) An overview of the WaterGAP model. Dialogue on Water and Climate (WATCLIM) 1(1):4

Udo de Haes HA, Finnveden G, Goedkoop M (2002) Life cycle impact assessment: striving towards best practice vol 1. 1st edn. Society of Environmental Toxicology & Chemist Brussels

De Schryver AM, Brakkee KW, Goedkoop MJ, Huijbregts MAJ (2009) Characterization factors for global warming in life cycle assessment based on damages to humans and ecosystems. Environ Sci Technol 43(6):1689–1695

Downing RJ, Ramankutty R, Shah JJ (1997) Rains-Asia: an assessment model for acid deposition in Asia. Directions in development, 1st edn. World Bank Publications, Washington, DC

Guinee JB, Marieke G, Heijungs R (2001) Life cycle assessment: an operational guide to ISO standards. Life Cycle Assessment: An Operational Guide to ISO Standards 1(1):19

ILCD (2010) Framework and requirements for life cycle impact assessment models and indicators. In: Centre JR (ed) International reference life cycle data system handbook

IPCC (2007) IPCC fourth assessment report: climate change 2007

Liu Y, Nie Z, Sun B, Wang Z, Gong X (2010) Development of Chinese characterization factors for land use in life cycle impact assessment. Sci China Technol Sci 53(6):1483–1488

Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 43(11):4098–4104

PORL (2008) Eutrophication Modeling of Singapore Waters. Physical Oceanography Research Laboratory. http://www.porl.nus.edu.sg/main/research/neutro-wqm. Accessed 29 August 2010

Roper LD (1976) Depletion theory. Depletion Theory 1(1):6

Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, Van De Meent D, Hauschild MZ (2008) USEtox—The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess 13(7):532–546

Tan BHR (ed) (2003) Life cycle assessment for green productivity: an Asian perspective, vol 1, 1st edn. Asian Productivity Organisation, Singapore